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Coupling between satellite dwarfs and the Milky Way warp

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Abstract. The perturbations of satellite galaxies, in particular the Large Magellanic Cloud (LMC), have been repeatedly proposed and discounted as the cause of the Milky Way warp. While the LMC may excite a wake in the Galactic dark matter halo that could provide sufficient torque to excite a warp of the observed magnitude, its orbit may be incompatible with the orientation of the warp's line of nodes. The Sgr dSph galaxy has an appropriately-oriented orbit, and due to its closer orbit may produce a stronger tidal effect than the LMC. Evidence that Sgr may be responsible for the warp comes from its orbital angular momentum, which has the same magnitude as the angular momentum of the warped component of the Galactic disk and is anti-aligned with it. We have run high resolution numerical N-body simulations of Sgr-sized satellites around a Milky Way-sized disk to test this idea. Preliminary results suggest that Sgr-sized satellites can indeed excite warps with properties similar to that observed for the Milky Way.

1. Introduction

Warped galactic disks are common phenomena; Reshetnikov & Combes (1998) find that half of all disk galaxies have observable warps. This has been a long-standing theoretical problem because isolated warps are not long-lived (e.g. Hunter & Toomre 1969). Therefore, there must either be a method of stabilizing warps so they are long-lived, or they must be generated frequently. The existence of apparently isolated strongly warped galaxies, such as NGC 5907, has led many authors to look for a universal method of stabilizing warps (e.g. Sparke & Casertano 1988; López-Corredoira, Betancort-Rijo, & Beckman 2002). However, with deeper photometry some of those galaxies, such as NGC 5907, now appear to be less isolated than previously thought (Shang et al. 1998). Therefore, it may be that there is no universal mechanism that stabilizes warps, but rather each galaxy reacts to the specific perturbations caused by the mass distribution in its immediate environment.

The Milky Way is a warped galaxy, with the warp seen in neutral hydrogen (Diplas & Savage 1991), dust (Freudenreich et al. 1994), and stars (Drimmel, Smart, & Lattanzi 2000). The Magellanic Clouds, as the most massive perturbers in the Galactic neighborhood, are an obvious candidate for causing the warp. Although Hunter & Toomre (1969) demonstrated that their direct torque is insufficient to cause the Milky Way warp, Weinberg (1998) proposed that the wake generated by the LMC in the Galactic dark matter halo could amplify its effects. Tsuchiva (2002) has performed simulations that suggest that if the Milky Way's halo is very massive, the LMC could indeed excite a large enough warp after 6 Gyr. However, Garcia-Ruiz, Kuijken, & Dubinski (2002) noted that a satellite on a fixed orbit generates a warp whose line of nodes is in the plane of the satellite's orbit, while the Milky Way's line of nodes is orthogonal to the LMC orbital plane. While they did not take precession or sinking of the satellite into account, the low resolution but fully self-consistent simulations of Huang & Carlberg (1997) also indicate that as satellites sink, they lose angular momentum to both the disk and the halo, which causes the disk to tilt and warp toward (away) from the plane of the satellite's orbit for satellites in prograde (retrograde) orbits.

The Sgr dSph, whose orbital plane intersects the Galactic line of nodes (Ibata et al. 1997), might therefore be a good candidate for causing the Milky Way's warp (Lin 1996). Although much less massive than the LMC, its smaller galactocentric radius could strongly amplify its effect (Bailin 2003). Indeed, Ibata & Razoumov (1998) have performed simulations in which they passed a satellite on Sgr's orbit through a gas disk embedded in a static Milky Way potential, and found that for a massive enough satellite, the gas disk was noticeably perturbed and warped.

In this proceeding, we examine some dynamical evidence that Sgr may be responsible for the warp, and present some preliminary N-body simulations of satellite-disk interactions with the aim of modelling the Sgr-Milky Way system.

2. Angular Momentum in the Warp and Satellites

A torque is a transfer of angular momentum. A torque between two components of a system will couple their angular momenta.

The angular momentum of the warped component of the disk can be estimated by using a tilted ring model, where the angular momentum in a ring at radius R of width dR, surface density $\Sigma(R)$ and circular velocity $v_c(R)$ has angular momentum

$$dL = 2\pi R^2 v_c(R) \Sigma(R) dR$$

directed toward the rotation axis. The component of this which is due to the warp, i.e. the component not perpendicular to the Galactic plane, is $(2-8) \times 10^{12} \ M_{\odot}$ kpc km s⁻¹, for a range of reasonable Galactic mass models (Bailin 2003).

The orbital angular momenta of satellite galaxies can be calculated when they have measured proper motions. The angular momentum of Sgr is $(2-8) \times 10^{12} M_{\odot}$ kpc km s⁻¹, anti-aligned with the warp angular momentum, while the other satellites have angular momenta that span 3 orders of magnitude and cover a wide range of directions (Bailin 2003). The coincidence of the angular

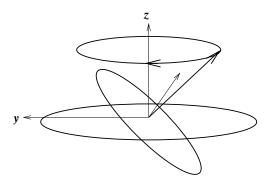


Figure 1. The galactic disk lies in the xy plane. The satellite's angular momentum, denoted by the bold vector, initially lies in the yz plane and precesses counterclockwise around the z axis.

momenta of Sgr and of the Milky Way warp suggests that they are coupled, i.e. that Sgr is responsible for the warp.

3. N-body Simulations

Previous simulations of the interaction between Sgr and the Milky Way disk have suffered from too low resolution (Huang & Carlberg (1997) had 80,000 particles in their galaxies while Weinberg (1998) estimates that at least 10⁶ particles are necessary to resolve the halo wake), assumed static potentials (Ibata & Razoumov (1998) did not allow the halo or the satellite to respond dynamically, artificially restricting the degrees of freedom), or explored a different region of parameter space than that appropriate for the Sgr–Milky Way system (Tsuchiya (2002) was concerned with the effects of the LMC, not Sgr).

Our simulations presented here consist of a Milky Way based on model 3 of Dehnen & Binney (1998). The halo has a mass of $8.96 \times 10^{11}~\rm M_{\odot}$ represented by 1048576 collisionless particles, while the luminous (disk and bulge) component has a mass of $4.82 \times 10^{10}~\rm M_{\odot}$ represented by 1048576 collisionless particles. The satellite is modelled by a single particle with mass $2 \times 10^9~\rm M_{\odot}$, at the upper range of the estimated mass of Sgr (Helmi & White 2001). The satellite was placed at its apogalacticon at 70 kpc and evolved forward using the GADGET code (Springel, Yoshida, & White 2001) on an orbit with a perigalacticon at 12 kpc (Helmi & White 2001) and inclined 45°to the galactic plane. One simulation was performed with the satellite on a prograde orbit and one with the satellite on a retrograde orbit (a polar orbit simulation was also run but suffered from numerical issues and so is not included).

Near perigalacticon, the satellite is exposed to the flattened potential of the galactic disk, causing its orbit to precess. In the simulation coordinates, the projection of the satellite's orbital angular momentum is initially along the -y axis. As it precesses, it acquires $-L_x$ and $+L_y$ (see Figure 1). In the retrograde case, all of this angular momentum is acquired by the disk, whereas in the prograde case the disk only acquires the x component while the y component is

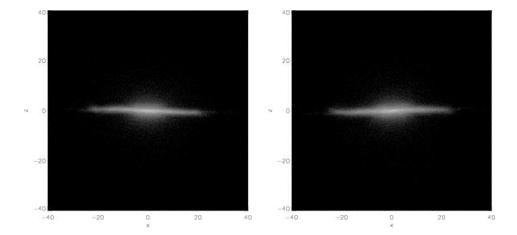


Figure 2. Simulation of the Galactic disk after the satellite has orbited for 3.1 Gyr. The satellite was placed on a prograde (*left*) (retrograde (*right*)) orbit inclined 45° to the disk. Intensity represents log(projected surface density).

absorbed by the halo. This demonstrates the importance of including a live halo which can exchange angular momentum with the other components – without a live halo, the behaviour of the system would be qualitatively different.

Figure 2 shows a snapshot of the simulations after 3.1 Gyr, shortly after the third perigalactic passage. In both cases, a warp-like feature has formed. The warps are strongest shortly after the perigalactic passages. The angular momentum transfer is strongly peaked at perigalacticon, causing the disk to tilt in discrete jerks that send out vertical bending waves which are seen as warps. These warps are dynamical, and not long-lived. Evidence that the Milky Way's warp is a dynamical warp comes from Drimmel et al. (2000), who found that while the Galactic stellar distribution is warped, the dynamics are not consistent with a stationary or uniformly precessing warp. However, although the simulated warp is not stationary, it appears frequently. The warp moves outward at the group velocity of bending waves in a stellar disk, which scales as $\pi G \Sigma / \Omega$ for surface density Σ and rotational velocity Ω (Hofner & Sparke 1994), or $\sim 30 \; \rm kpc \; Gyr^{-1}$ near the solar circle. Since the period of Sgr's orbit is approximately 1 Gyr (Helmi & White 2001), the warp reaches the end of the disk shortly before the next satellite passage warps it anew. Thus if satellites in orbits like Sgr are common around disk galaxies, a large fraction of disks could appear warped at any given time even though the warps are not themselves long-lived.

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